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DETERMINING THE SOUND FIELD PRODUCED BY THE MANEUVERING OF JET AIRCRAFT

by
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DETERMINATION OF THE ACOUSTIC FIELD GENERATED BY A JET AIRCRAFT IN MOTION (DETERMINATION DU CHAMP SONORE PRODUIT PAR L'EVOLUTION DES AVIONS A REACTION).

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The relation between the global sound pressure field generated by an axisymmetrical stationary jet and that produced by a moving jet, observed from a fixed point on the ground, is studied through the introduction, in the generalized sound pressure equation, of a new convection parameter derived from the Ribner expression. This new equation confirms the known results in the maximum sound direction and gives a better value in the other directions. The results of the analytical study, confirmed by many experimental results, show that, in the directions other than that of maximum pressure, the relative speed is not the significant parameter for determining the local total sound pressure level. **(Author)**

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IV

Summary

The relation between the total sound-pressure field emitted by a *stationary* rotating jet and the sound field from that same jet *in motion*, observed at a fixed point on the ground, is studied by introducing into the generalized equation for the local over-all sound-pressure level, whose form is recalled, a new convection index derived from the Ribner expression

$$[(1 - M_c \cos \theta)^2 + \alpha^2 M_c^2]^{-5/2} \quad (1 + \cos^4\theta).$$

The new equation confirms the earlier findings in the direction of maximum acoustic radiation θ_M and improves the predictability of the noise to be expected in the other directions.

The influence of the flight speed on the sound emission is demonstrated over a broad range of angles (from 20 to 160° with respect to the jet axis). Deduced from it are the relation between the convection effect of the vortices in stationary and moving jets, and the variation of the acoustic power produced by propulsion of the jet through the atmosphere.

The results of the analytic study, confirmed by many experimental findings, have shown that at the different angles of θ_M the relative speed is not the significant parameter to use for determining the levels of the local over-all sound pressure.

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DETERMINING THE SOUND FIELD PRODUCED BY THE MANEUVERING OF JET AIRCRAFT

BY

MICHEL KOBRYNSKI

Precalculating accurately in the design stage the noise that an aircraft will generate has become a necessity both for the planning of optimal trajectories and to meet noise-level certification requirements. The amplitude and spectrum of the sound-pressure field at ground level have to be known as functions of the engine and flight parameters, and during the maneuvering of the aircraft, if we are to determine, for example, the discomfort level in terms of effective PNDB.

One method of precalculating the sound field produced by stationary and moving rotating jets, which we have proposed in previous papers, consists in first limiting the calculation to the direction of maximum acoustic radiation[1], then extending it over a large range of angles, from 20 to 160°, with respect to the jet axis[2].

This method of calculating the noise of straight turbojets, in dry or postcombustion operation, is reexamined and supplemented in this paper, particularly through the introduction of a new form of convection factor for the vortices in the jet.

1. *REVIEW OF EARLIER RESULTS*[1,2]

We let α be the angle of ascent of a jet aircraft [Figure 1], i its incidence, β the setting of the jets, θ the angle formed by the axis of the jet and the sound ray directed toward an observation point O, ψ being the angle between the sound ray and the horizontal. These angles are related through the formula: $\theta = \pi - (\psi + \alpha + \beta + i)$. (1)

Figure 1:

Trajectory of the aircraft in flight. Angles considered.

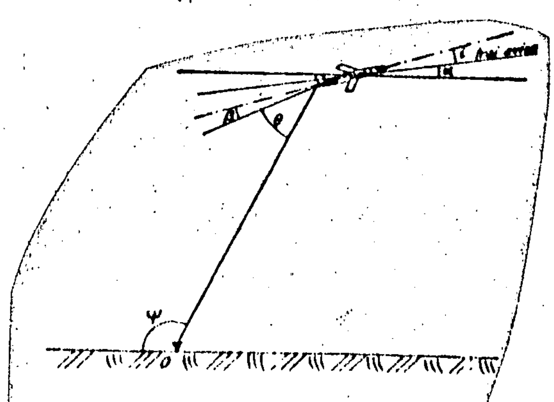

Fig. 1
Trajectoire de l'avion en vol.
Angles considérés.

Taking as the time origin the arrival of the aircraft at the vertical of the point O, we can determine the position of the aircraft at the instant at which the sound received at O was emitted, and the time of its emission, as a function of the altitude of the arrival at 0, of the speed of the aircraft, and of the aforecited angles. The variation of the noise levels recorded as a function of the time can then be referred to the angle θ, as shown in Figure 2.

Figure 2: Jet airplanes in flight. Variation of the linear over-all sound pressure recorded as a function of the time or of the angle.

1- direction of flight

2- degrees

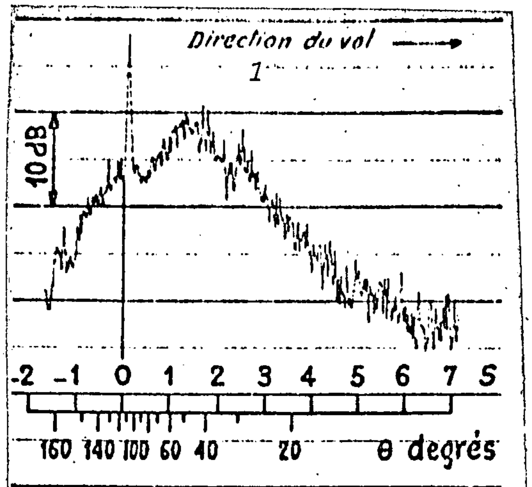

Fig. 2
Avions à réaction en vol. Variation du niveau de pression sonore globale linéaire sur la trace en fonction du temps ou de l'angle.

We propose to determine at the point 0 or at a point taken on the perpendicular to the track the over-all noise levels, and by the bands of frequencies emitted by the jet as a function of the angle θ, from 20 to 160°, and especially the noise levels associated with the angle of maximum acoustic radiation θ_M. Of course the calculation also makes it possible to obtain the sound field produced by stationary jets.

Calculation of the noise level involves first the acoustic power generated by the jet, for which the general expression is

$$W = K \frac{\rho_j^2 S V_j^8 \left(1 - \frac{V_a}{V_j}\right)^4}{\rho_a C_a^5}, \qquad (2)$$

where ρ_j is the volumetric density of the gases of the expanded jet, ρ_a that of the surrounding air, V_j the velocity of the gases ejected through the surface S, C_a the speed of sound in the surrounding air, V_e the propulsion speed of the aircraft. The coefficient K is equal to 1.8×10^{-4} [see ref. 1]. From that power we deduce the spatial mean level (a source assumed isotropic) on a reference sphere, with a selected radius R_o of 30 m, centered on the jet nozzle, and then the over-all sound-pressure level N_θ at a point characterized by the angle θ, the directivity being given by the *convection factor*. Next, the result obtained is introduced into the calculation of the sound-pressure levels associated with the frequency bands (by octave, for instance) by bringing in the curves of the generalized acoustic spectrum, characteristics of the considered directions [see Section 4]. These noise levels, calculated for $R_o = 30$ m, are finally corrected by applying to them the geometric and molecular attenuations corresponding to the lengths of the considered sound rays.

The expression for N_θ is [see ref. 2, equation 14]

$$N_\theta = 10 \log_{10} \frac{\rho_j^2 \, S M_c^8 \left(1 - \frac{M_v}{2M_c}\right)^4}{\left[1 - M_c\left(1 - \frac{M_v}{2M_c}\right)\cos\theta\right]^\eta} + C, \qquad (3)$$

where M_c is the convection Mach number of the vortices in the jet $\left(M_c = \frac{1}{2}\frac{V_j}{C_a}\right)$, $M_v = V_e/C_a$ the flight Mach number, and the exponent η

Translator's Note: Subscript v = vol (French for "flight").

of the convection factor is determined with the experimental formula

$\eta = 16\ M_c/(6\ M_c^3 + 1)$.

At the reference distance $R_o = 30$ m the cumulative constant C assumes the value 138 dB for stationary jets, 140 dB for jets in flight. The validity of equation (3) is limited to the angles $\theta > \theta_M$, where θ_M is the angle of maximum acoustic radiation, given by the experimental formula

$$\theta_M = 24\ M_c + 13\ . \tag{4}$$

Translator's Note: The reader is warned that the translator is working from a copy of the French original whose legibility leaves much to be desired. The translator is not sure, for example, whether the last number above is really 13 or (in the French) a blurred 18.

When we note, however, that the polar curves for the variation of the over-all noise levels are symmetrical, with satisfactory approximation, on both sides of θ_M in the $\pm\ 20^o$ angle range, which is sufficient in our calculations, we can adopt for each angle $\theta < \theta_M$ the value θ' of the θ angle symmetrical with respect to θ_M, i.e.,

$$\theta' = 2\theta_M - \theta\ . \tag{5}$$

In expression (3), which gives the value of N_θ, the denominator is the convection factor in a form derived from the one given by Lighthill[3], with an experimental modification of the exponent. We propose in this paper to determine *a new convection factor*, based on a more elaborate expression proposed by Ribner.

2. *CONVECTION FACTOR*

2.1 *Stationary Jets*

From the works of Lighthill[3] and Ffowcs-Williams[4] we know that, for a stationary jet of low Mach number, the directional distribution of the sound intensity follows the emission laws for aerodynamic quadruplets driven into the jet with a convection velocity $V_c = M_c C_a$. The convection factor obtained has the form

$$(1 - M_c \cos \theta)^{-5} \; . \tag{6}$$

Obviously the amplification predicted by this factor cannot increase indefinitely with M_c and become infinite for

$$M_c \cos \theta = 1 \; , \tag{7}$$

which is why, in order to satisfy the experimental values, we have replaced the exponent -5 , given in expression (6), with the variable exponent η . Also, for various reasons, and when (7) was taken into account, the validity of the convection factor thus expressed was restricted to the angles θ falling within the range $\arccos 1/M_c > \theta \geqslant \theta_M$.

Subsequent studies by Ffowcs-Williams[5] and Ribner[6] led to a modified expression for the convection factor which eliminates the singularity (7):

$$\left[(1 - M_c \cos \theta)^2 + \left(\frac{\omega_s \ell}{\sqrt{\pi}\, C_a} \right)^2 \right]^{-5/2} , \tag{8}$$

where ω_s is a pulsation characteristic of the turbulence of the stationary jet, l the correlation radius, or l^3 the "effective volume of the vortex" of coherent radiation (the new term $\frac{\omega l}{?\, C_a}$ being the Damkohler parameter).

When we consider that the preferential orientation of the systems of quadruplets in the jet introduces the factor[6]

$$1 + \frac{\cos^4\theta + \cos^2\theta}{2} \simeq 1 + \cos^4\theta \,, \tag{9}$$

the factor of the noise's over-all directivity is given by[6]

$$\left[(1 - M_c \cos\theta)^2 + \alpha^2 M_c^2\right]^{-5/2} (1 + \cos^4\theta) \,, \tag{10}$$

$$\text{with} \quad \alpha = \frac{\omega_s l}{\sqrt{\kappa}\, V_c} \,. \tag{11}$$

Comparing expression (10) to the experimental polar distribution of the levels of over-all sound pressure for stationary jets led us, through iteration, to a value of α_s^2 expressed with good approximation by

$$\alpha_s^2 = 0.45 \frac{1}{M_c^2} + 0.75 \frac{\log M_c}{M_c} \,, \tag{12}$$

and this value is retained in the calculations that follow.

2.2 *Moving Jets*

With respect to the atmosphere, in which the sound waves are propagated, the convection Mach number is $M_c - \frac{1}{2} M_v$. (13)

We shall designate as α_v the coefficient (11) for a jet in flight, letting ω_v be the characteristic pulsation associated with that jet's

Translator's Note: ? = illegible.

turbulence.

Also, in the system of moving coordinates, tied to the jet, which we are to adopt here, the convection velocity becomes $V_c(1 + \frac{M_v}{2M_c})$. Assuming that the correlation radius remains unchanged, we can write:

$$\boxed{\alpha_v = \frac{\omega_v \ell}{\sqrt{\pi} V_c \left(1+\frac{M_v}{2M_c}\right)}} \quad . \tag{14}$$

The ratio between the characteristic pulsations associated with the turbulence of stationary jets ω_s and moving jets ω_v , respectively, is given by

$$\boxed{\frac{\omega_v}{\omega_s} = \left(1+\frac{M_v}{2M_c}\right)^2} \qquad \text{for } \frac{M}{2M_c} < 0.3 \ , \tag{15}$$

as we have already shown [see ref. 1]. From (14), (15) and (11) we get:

$$\alpha_v = \alpha_s \left(1 + \frac{M_v}{2M_c}\right) \quad . \tag{16}$$

Combining (10), (13) and (16), and noting that in a given direction the acoustic radiation emanating from jets is reduced to that of the vortices, whose emission comes simultaneously, the reduction factor being $(1 + M_v \cos\theta)^{-1}$, as determined by Ff.-Williams[4] purely geometrically, we can say that the directional intensity of the noise of moving jets is given by

$$\boxed{\left\{\left[1-M_c\left(1-\frac{M_v}{2M_c}\right)\cos\theta\right]^2 + \alpha_s^2 M_c^2\left(1+\frac{M_v}{2M_c}\right)^2\right\}^{-5/2}(1+M_v\cos\theta)^{-1}(1+\cos^4\theta)} \ , \tag{17}$$

in which α_s^2 is given by (12).

This expression, valid at the angles $\theta \geqslant \theta_M$, where θ_M is determined with formula (4), reduces to (10) for $M_v = 0$.

For the angles $\theta < \theta_M$ the conditions for use of this expression are set forth in Section 1.

3. *LEVELS OF POLAR OVER-ALL SOUND PRESSURE*

3.1 *Stationary Jets*

The method for calculating the levels of the polar over-all sound pressure produced by stationary jets N_θ includes the following steps:

- determining the emitted acoustic power from the jet's thermodynamic characteristics;
- calculating the spatial mean sound pressure in a remote field (pressure produced by the isotropic distribution of that power);
- introducing the amplification of this pressure as a function of the angle θ , described by the *convection factor*.

The over-all acoustic power emitted by stationary jets W_s is given by formula (2) with $V_e = 0$. In a free field the mean square of the sound pressure at the distance R is

$$\overline{p^2} = \frac{\rho_a C_a W_s}{4? R^2} . \tag{18}$$

The level of spatial mean sound pressure $<N_m>$ is found from (18) and (2). With our notation:

$$<N_m> = 10 \log_{10} \rho_j^2 \, SM_c^3 + C_1 , \tag{19}$$

Translator's Note: *Above formula only semilegible in the French.*

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where C_1 is a cumulative constant whose value is 141 dB in a free field, at the distance $R = R_o = 30$ m.

We have assumed that the sound source and the observation point are both situated in the unbounded medium, and that the distance between the source and the point is large compared to the wavelength of the lowest measured frequency and compared to the characteristic dimension of the source itself (condition for a remote acoustic field). Actually, the measurements are made near the ground, and the presence of the more or less reflecting ground perturbs propagation of the sound waves between the source and receiver. The received acoustic spectrum is modified by the interference between the sound rays.

The study shows that the ground effect manifests itself through an increase of the over-all noise level, which may vary from 3 to 6 dB. Considering the conditions encountered in practice, we adopt the generally assumed value of 3 dB.

Under these conditions the cumulative constant C_2 will have as its value $C_1 + 3 = 144$ dB, and, when we bring in the ground effect, equation (19) is written

$$\langle N_m \rangle_s = 10 \log_{10} \rho_j^2 \, S M_c^3 + C_2 \tag{20}$$

for $R_o = 30$ m.

Translator's Note: Again, caution! French only semilegible.

We now introduce into (20) the combined factors of sound-intensity amplification due to the convection velocity of the vortices in the jet and to the preferential orientation of the quadruplets, expressed by (10), and we get the polar local over-all sound level:

$$\boxed{N_{\theta_s} = 10 \log_{10} \frac{\rho_j^2 \, S M_c^8 \, (1 + \cos^4\theta)}{\left[(1 - M_c \cos\theta)^2 + \alpha_s^2 M_c^2\right]^{5/2}} + C_s}, \tag{21}$$

where α^2 is replaced by α_s^2, as determined by (12).

Let us note that the *linear* local sound-pressure level is given by

$$N_{\theta_s} + 10 \log_{10} \frac{\sin^2\theta}{\cos^2(\alpha + i + \beta)} , \tag{22}$$

α, i and β having been defined in Section 1.

3.2 Moving Jets

Calculation of the levels of the polar over-all sound pressure produced by moving jets will be done first at a point defined within the reference system tied to the jet, then within a reference system tied to the presumably motionless atmosphere or to the ground.

We let $N^*_{\theta_v}$ be the noise level N_{θ_v} in the first reference system.

As with the stationary jet, the calculation of $N^*_{\theta_v}$ brings in the acoustic power expressed by (2), the moving jet's spatial mean sound-pressure level $\langle N_m \rangle_v$ in a free field, which according to (19) will be

$$\boxed{\langle N_m \rangle_v = 10 \log_{10} \rho_j^2 \, S M_c^8 \left(1 - \frac{M_v}{2 M_c}\right)^4 + C_1}, \tag{23}$$

where C_1 is the cumulative constant of the stationary jet, and finally the sound-intensity amplification due to the convection velocity and other causes, as expressed by (17).

Once all the calculations have been made and we have brought in the ground-effect constant, we get the analytic expression:

$$\boxed{N^{\bullet}_{\theta_v} = 10 \log_{10} \frac{\rho_j^2 \, S M_c^8 \left(1 - \frac{M_v}{2M_c}\right)^4 \left(1 + \cos^4\theta\right)}{\left\{\left[1 - M_c\left(1 - \frac{M_v}{2M_c}\right)\cos\theta\right]^2 + \alpha_s^2 M_c^2 \left(1 + \frac{M_v}{2M_c}\right)^2\right\}^{5/2} \left(1 + M_v \cos\theta\right)} + C_2}, \tag{24}$$

where α_s^2 is given by (12), and $C_2 = 144$ dB for $R_o = 30$ m.

Let us note that, as in the case of the stationary jet, the angles involved in the convection index will be determined with formula (5) for $\theta < \theta_M$, where θ_M is given by (4).

Equation (24) indicates the over-all level of the noise *emitted* by the moving jet (axes tied to the aircraft in flight), whereas the *measured* noise level (axes tied to the ground) depends on the variation of the sound ray* R due to the geometric and molecular attenuation of the noise (a dB per meter).

* *Translator's Note: French "rayon" = English "ray" AND/OR "radius." This author's intended meaning not always clear.*

Also, we have to bring in the width of the passband in which the analyzer is operating, hence the need to introduce into (24) corrections for the Doppler effect.

We let f_{ev} be a characteristic frequency emitted by the jet in flight so that it would be measured at a point in space referred to the moving coordinates tied to the aircraft. At the point referred to the fixed coordinates the measured frequency will be the apparent frequency f_a transformed from f_{ev}

by the Doppler effect, i.e., $$f_{ev}/f_{a} = 1 + M_v \cos\theta \; . \tag{25}$$

If Δf_i is the normalized width of the frequency bands measured in the range i, the corresponding sound intensity has been emitted in a band of width $\Delta f_i(1 + M_v \cos\theta)$, which means a noise-level correction expressed as $10 \log_{10}(1 + M_v \cos\theta)$.

Under these conditions, if N_{θ_v} is the local over-all level of the noise received at a fixed point on the ground at the distance R, then

$$\boxed{N_{\theta_v} = N^*_{\theta_v} + 10\log_{10}\left(1 + M_v \cos\theta\right) - 20\log\frac{R}{R_0} - a(R - R_0)} \; , \tag{26}$$

where $N^*_{\theta_v}$, determined with (24), is the polar over-all level of the noise emitted at the distance R_0.

The coefficient a being a function of the frequency, calculation of the term $a(R - R_0)$ requires that we know the acoustic spectrum associated with $N^*_{\theta_v}$. That spectrum is determined by the method described in Section 4.

Since the general form of the expression that gives us N_{θ_v} has been defined, let us simplify matters by setting $R = R_0$. Combining equations (26) and (24), we get

$$\boxed{N_{\theta_v} = 10\log_{10}\frac{\rho_j^2\, S M_c^8\left(1 - \frac{M_v}{2M_c}\right)^4\left(1 + \cos^4\theta\right)}{\left\{\left[1 - M_c\left(1 - \frac{M_v}{2M_c}\right)\cos\theta\right]^2 + \alpha_s^2 M_c^2\left(1 + \frac{M_v}{2M_c}\right)^2\right\}^{5/2}} + C_8} \; . \tag{27}$$

For $M_v = 0$ we again obtain equation (21), which gives the N_{θ_s} level for a stationary jet.

3.3 *Effect of the Jet's Propulsion Speed on the Sound Field*

The noise-level reduction, depending on the direction θ, produced by the flight Mach number becomes evident when we combine equations (27) and (21). We get:

$$N_{\theta_s} - N_{\theta_v} = 10\log_{10}\frac{\left\{\left[1-M_c\left(1-\frac{M_v}{2M_c}\right)\cos\theta\right]^2+\alpha_s^2M_c^2\left(1+\frac{M_v}{2M_c}\right)^2\right\}^{5/2}}{\left[(1-M_c\cos\theta)^2+\alpha_s^2M_c^2\right]^{5/2}\left(1-\frac{M_v}{2M_c}\right)^4}. \qquad (28)$$

Numerical solution of this expression, accomplished by assigning many discrete values to the Mach numbers M_c and M_v, has shown that in the direction of maximum acoustic radiation θ_M, determined with (4), and *in that singular direction*, with good approximation we can write

$$\left\{\frac{\left[1-M_c\left(1-\frac{M_v}{2M_c}\right)\cos\theta_M\right]^2+\alpha_s^2M_c^2\left(1+\frac{M_v}{2M_c}\right)^2}{(1-M_c\cos\theta_M)^2+\alpha_s^2M_c^2}\right\}^{5/2}\left(1-\frac{M_v}{2M_c}\right)^4 \approx 1, \qquad (29)$$

i.e., in the direction θ_M the ratio of the convection factors for a stationary and moving jet, respectively, is approximately equal to the factor of reduction of the acoustic power due to the fact that the jet is moving: $\left(1-\frac{M_v}{2M_c}\right)^{-4}$.

Consequently, by replacing the convection factor in (27) with its particular value from equation (29), we obtain an approximative expression for the polar *maximum* over-all sound-pressure level for the moving jet N_{θ_M}, which is

$$N_{\theta_M} = 10\log_{10}\frac{\rho_j^2 S\left(M_c-\frac{1}{2}M_v\right)^8(1+\cos^4\theta)}{\left[(1-M_c\cos\theta_M)^2+\alpha_s^2M_c^2\right]^{5/2}} + C_1.$$

This result, which is close to equation (21) for a stationary jet, shows that in the direction θ_M the level of the polar over-all maximum sound pressure produced by the moving jet can be determined with either equation (27) or (21), in which the jet's *relative speed* figures. This indicates that in the maximum-noise direction, and *in that direction only*, the relative speed can be used as a parameter for calculating the noise level of a jet in flight.

3.4 *Experimental Verification of Equation (27)*

We made a large number of measurements of the noise emitted by different types of jet aircraft (*MIRAGE IV*, *CARAVELLE I*, *GLOSTER*, *METEOR*, *FOUGA MAGISTER*) at a fixed point and in flight.

In this paper our earlier reported experimental data[1,2] are supplemented with more recent findings.

Strictly speaking, a comparison of the measured with the calculated noise levels would require the introduction of a correction to allow for the ground effect, which can be calculated in the case of a perfectly reflecting plane.[7] This reflection cannot be assumed when it comes to our experiments, hence the measured levels have not been corrected for it, either over all or by octave.

The experimental verifications of equation (27) were made for stationary jets ($M_v = 0$) and jets in flight at different angles θ measured from the angle θ_M , at 20° intervals, i.e.,

$$\theta_M\ ,\ \theta_M + 20^\circ, \ldots\ldots,\ \theta_M + 100^\circ \text{ and } \theta_M - 20^\circ .$$

In both cases the polar over-all noise levels are reduced to $R_o = 30$ m by introducing the geometric and molecular attenuation, the corrections adopted being those of the S.A.E.[8], which were then normalized with the term $10 \log_{10} \rho_j^2 s$ and finally, in the case of groups of jets, corrected with the term $5 \log n$ (stationary jet) or $10 \log_{10} n$ (jet in flight), n being the number of the aircraft's turbojets.

Be it noted that the noise levels of the aircraft in flight were determined from the curves giving the variation of the linear noise levels recorded at a fixed point and of the distance of the aircraft from that point at the instant of sound emission. Then, these noise levels were corrected with formula (28), which represents the effect of the moving jet's propulsion speed, so that the results obtained could be compared with those for stationary jets.

3.4.1 Stationary Jets

Figures 3-9 compare the measurement results with the calculations for each of the adopted angles θ . In those figures the polar over-all noise levels of the stationary jets are indicated with little crosses (×), and each of the curves was plotted with equation (27) for $M_v = 0$ for the values of θ specified above.

It should be noted that in the direction $\theta_M - 20^\circ$ the angle θ of the convection factor has been replaced with the angle θ' determined with formula (5).

For all the directions considered, the agreement of the experimental findings with the theory is seen to be satisfactory.

3.4.2 M o v i n g J e t s

Figures 3-9 compare the normalized over-all noise levels of jets in flight, expressed as $N_\theta + \Delta N_{\theta_v} - 10 \log_{10} \rho_j^2 s$, with the theoretical curves given by equation (27) for $M_v = 0$ [indicated by dots].

This comparison has shown that the correction for the jet's propulsion speed, given by formula (28), is satisfactorily verified only for angles θ between $\theta_M - 20^\circ$ and $\theta_M + 40^\circ$ [Figures 3, 4, 5 and 9], i.e., for $\theta < ?/2$.

On the other hand, for the range of angles $?/2 < \theta < ?$ [Figs. 6-8] and for $M_c > 0.9$ approximately, the agreement between the normalized over-all noise levels of the jets in flight and equation (27) for $M_v = 0$ is better if the noise-level reduction due to the flight Mach number M_v, ΔN_{θ_v} is expressed as:

$$\Delta N_{\theta_v} = 10 \log_{10} \frac{\left\{\left[1 - M_c\left(1 - \frac{M_v}{2M_c}\right)\cos\theta\right]^2 + \alpha_j^2 M_c^2\left(1 + \frac{M_v}{2M_c}\right)^2\right\}^2 (1+\cos^2\theta)^{l(\alpha,g)}}{\left[(1 - M_c\cos\theta)^2 + \alpha_c^2 M_c^2\right]^{5/2}\left(1 - \frac{M_v}{2M_c}\right)^4}, \tag{30}$$

Figure 3: Polar over-all sound-pressure level of aircraft at fixed point, indicated by little crosses (×), and in flight, indicated by dots, in the direction [*symbol omitted---Transl.*] for R_o = 30 m. Theoretical curve for $\theta = \theta_M$.

Fig. 3
Niveaux de pression sonore globale polaire des avions au point fixe (repérés par des ×), et en vol, repérés par des •) dans la direction pour R_o = 30 m. Courbe théorique pour $\theta = \theta_M$

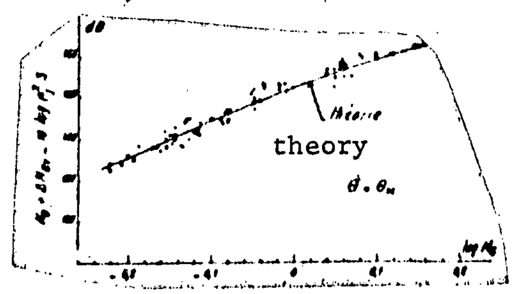


Figure 4: Measured and calculated polar over-all sound-pressure levels of the aircraft in the direction $\theta = \theta_M + 20^o$.

Fig. 4
Niveaux de pression sonore globale polaire polaire des avions dans la direction $\theta = \theta_M$ + 20° mesurés et calculés.

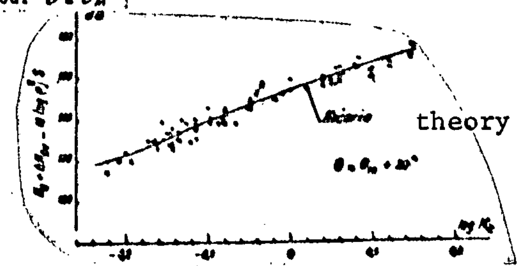


Figure 5: Measured and calculated polar over-all sound-pressure levels of the aircraft in the direction $\theta = \theta_M + 40^o$.

Fig. 5
Niveaux de pression sonore globale polaire des avions dans la direction $\theta = \theta_M$ + 40° mesurés et calculés.

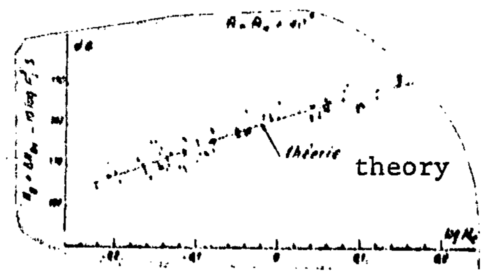


Figure 6: Measured and calculated polar over-all sound-pressure levels of the aircraft in the direction $\theta = \theta_M + 100^o$.

Fig. 6
Niveaux de pression sonore globale polaire des avions dans la direction $\theta = \theta_M$ + 100° mesurés et calculés.

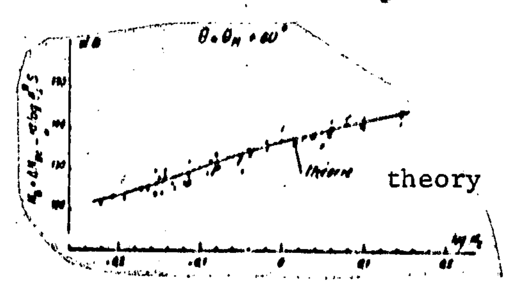


Figure 7: Measured and calculated polar over-all sound-pressure levels of the aircraft in the direction $\theta = \theta_M + 60^o$.

Fig. 7
Niveaux de pression sonore globale polaire des avions dans la direction $\theta = \theta_M$ + 60° mesurés et calculés.

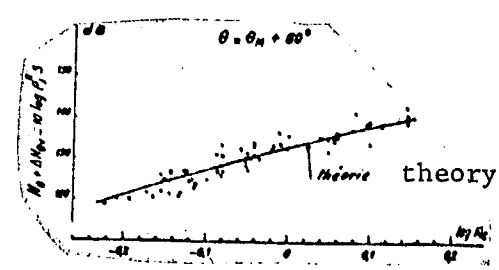


Figure 8: Measured and calculated polar over-all sound-pressure levels in the direction $\theta = \theta_M - 20^o$.

Fig. 8
Niveaux de pression sonore globale polaire dans la direction $\theta = \theta_M$ − 20° mesurés et calculés.

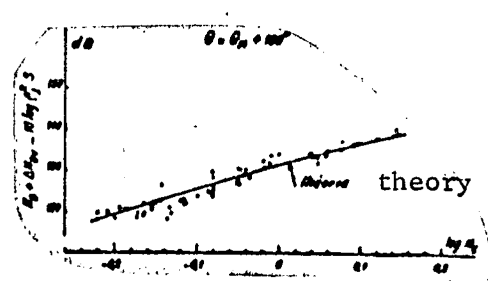


Figure 9: Measured and calculated polar over-all sound-pressure levels of the aircraft in the direction $\theta = \theta_M + 80^o$.

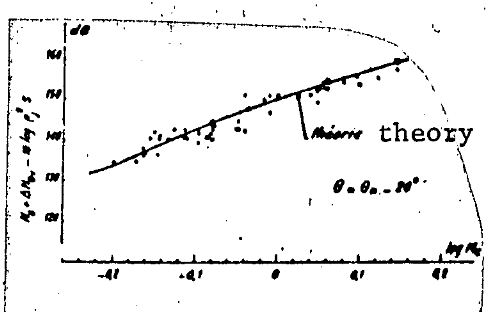


Fig. 9
Niveaux de pression sonore globale polaire des avions dans la direction $\theta = \theta_M + 80°$ mesurés et calculés.

where the exponent γ, originally equal to 5/2, is a function of M_V, of θ, and probably also of the pressure ratio (EPR), and where $\delta(i - j)$ is the Kronecker symbol ($\delta = f$ for $i = j$, $\delta = 0$ in the other cases).

Translator's Note: The symbols in the three lines above have been copied from a copy of the French that is all but completely illegible at this juncture. No guarantees can be offered with regard to them.

A study is in progress aimed at clarifying the relation between γ, M_V, and θ. For the time being, we have adopted for the angles $\theta \geqslant (\theta_M + 60^o)$ the value of γ given by the expression for the force

$$\gamma = \frac{3}{2} - \frac{2}{K} \text{ arc tan } (10 M_V - 3) . \qquad (31)$$

Since the value of the convection factor's exponent characterizes the nature of the aerodynamic source, it would seem that, for jets in flight and at angles θ greater than some 90^o, the predominant sound sources have directional characteristics not of quadruplets but of sources of order 1 and 0. This appears to be confirmed by the linear noise-level variation curve

[Figure 2], which at the considered angles shows an initial peak, which would be due to sources of order 0 and 1, then the second, usual peak attributed to the quadrupole sources.

3.5 *Final Form of the Expression for the Polar Over-all Sound-Pressure Levels*

According to the foregoing, the equation for the level of the local polar over-all sound pressure produced by stationary jets and jets in flight can assume the following final form:

$$N_\theta = 10 \log_{10} \frac{\rho_j^2 S M_c^8 \left(1 - \frac{M_v}{2M_c}\right)^4 \left(1 + \cos^4\theta\right)^{3(\gamma - 5/2)}}{\left\{\left[1 - M_c\left(1 - \frac{M_v}{2M_c}\right)\cos\theta_1\right]^2 + \alpha_s^2 M_c^2 \left(1 + \frac{M_v}{2M_c}\right)^2\right\}^\gamma} + C_2, \tag{32}$$

where α_s^2 is determined with formula (12), and $C_2 = 144$ dB at the reference distance $R_o = 30$ m.

The angle θ_i is equal to θ if $\theta_M \leq \theta < ?$*, θ_M being determined with (4). When $\theta < \theta_M$, θ_1 is given by (5).

---

* *Translator's Note: Severe legibility problems again. There are now some (uncertain) signs that what has thus far been vaguely resembling K may be "evolving" into* π.

In the case of a *stationary jet* $\gamma = \frac{5}{2}$. In the case of a *jet in flight*, and for $M_c > 0.9$, if $\theta < \frac{\pi}{2}$, $\gamma = \frac{5}{2}$; if $\theta = \frac{\pi}{2}$, $\gamma = 2 - \frac{1}{\pi}$ arc tan$(10\ M_v - 4)$; if $\theta > \frac{\pi}{2}$, $\gamma = \frac{3}{2} - \frac{2}{\pi}$ arc tan $(10\ M_v - 4)$;

if $M_c < 0.9$, $\gamma = 5/2$.

The levels of the linear over-all sound pressure (on a line parallel to the jet axis at a distance of 30 m from it) are given by equation (22).

4. *LEVELS OF LOCAL POLAR SOUND PRESSURE BY FREQUENCY BAND*

The polar noise levels associated with the frequency band i, N_{θ_i} are calculated by the method described in ref. 2, which brings in the generalized spectrum of sound pressure in the considered directions, as well as the over-all noise level N_θ. Let us recall its main features.

If $\psi(f)$ is the spectral density of the acoustic power, whose over-all value is P, we can write $P = \int_0^\infty \psi(f)\, df$.

Let us adopt the similarity relation $f \alpha \frac{V}{l}$, where V is a velocity characteristic of the jet, l a dimension characteristic of it.

In the remote acoustic field, if $\overline{p}^2$ is the mean square of the local

> *Translator's Note: The letter symbols in the French being handwritten, it is sometimes hard to tell whether an upper- or lower-case letter is intended.*

sound pressure, the preceding equation assumes the form $\boxed{\int_0^\infty \left[\frac{V}{L}\,\frac{p^2(z,\theta,f)}{p^2\,(z,\theta)}\right]\frac{L}{V}\,df = 1}$,

where Z is the distance between the sound source and the observation point.

The similarity relations $L \alpha D$ (D being the diameter of the jet in the plane in which the gases exit) and $V \alpha V_j$, as well as equations (15) and (25), lead us to a determination of the Strouhal number for the jet in flight:

$\boxed{S_n = \frac{(1+M_v \cos\theta)D}{\left(1+\frac{V_a}{V_j}\right)^{1} V_j} f_a}$, which for $M_v = 0$ reduces to its usual form

$$S_n = \frac{D}{V_j} f_{es} \quad . \tag{33}$$

In these equations f_a and f_{es} indicate the same center frequency of the normalized frequency bands.

For its part, the level of the dimensionless spectral density of sound pressure emitted by stationary jets ($M_v = 0$) and jets in flight is:

$$\boxed{K_i = N_{f_i} \left[N_\theta - 10 \log_{10} \frac{\left(1+\frac{V_a}{V_j}\right)^{1} V_j}{(1+M_v \cos\theta) D} \right]} , \tag{34}$$

account being taken of (15) and of the correction for the Doppler effect, which also involves the intensity [see Section 3].

In this expression N_{f_i} is the spectrum noise level determined with

$$N_{f_i} = N_{\theta_i} - 10 \log \Delta f_i , \tag{35}$$

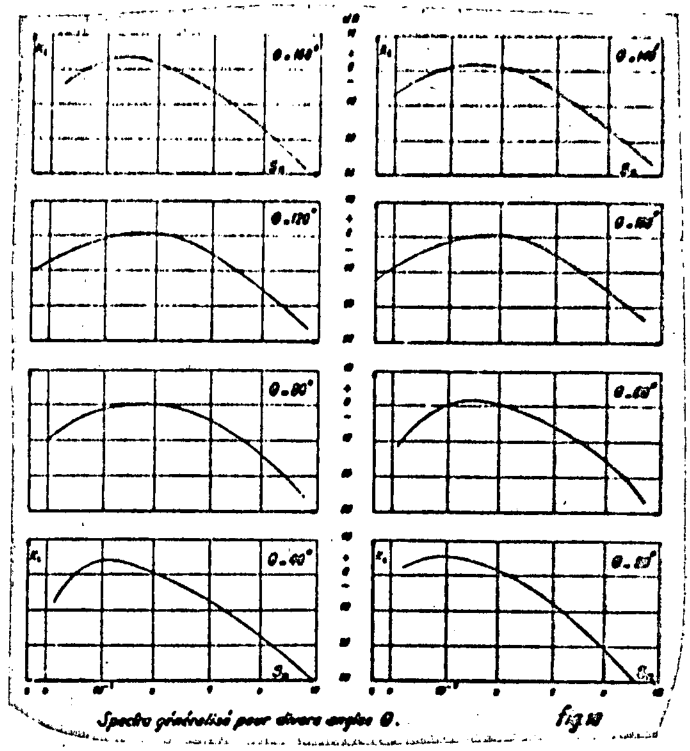
where Δf_i is the range of frequencies associated with the frequency band i .

The spectrum levels of the noise coming from different aircraft at a fixed point and in flight, and determined from the ground for the different angles θ, were expressed in terms of the coordinate system having (33) as abscissae, (34) as ordinates.

This experimental verification has shown[2] that the local acoustic spectra, thus generalized, do provide, with satisfactory approximation, a mean curve characteristic of the considered direction. Figure 10 gives these mean curves for angles θ varying by 20° from 20 to 160°.

Figure 10:

Generalized spectrum for different angles θ .



Returning to our calculation of the sound-pressure levels associated with the frequency bands, N_{θ_i}, if in (34) we replace N_{f_i} with the expression of it given by (35), we get $N_{\theta_i} = N_\theta - 10 \log_{10} \frac{(1+\frac{V_c}{V_i})^{2} V_i}{(1+M_v \cos\theta) D} + 10 \log_{10} \Delta f_i + K_i$.

In this formula N_θ is determined with equation (32), and positive or negative K_i is read on the ordinate of the generalized-spectrum curve

[Figure 10] for the considered angle θ .

5. *CONCLUSION*

The total field of the sound pressure on the ground produced by the maneuvering of jet aircraft is calculated by a method that brings in the thermodynamic characteristics of the jet, its propulsion speed V_e , as well as the generalized acoustic spectra for the considered directions.

This method---verified experimentally for the rotating jets issuing from straight turbojet engines with subcritical and slightly supercritical pressure ratios, and for values of the aerodynamic parameter V_e/V_j below 0.3---has confirmed the earlier findings in the direction of maximum acoustic radiation, and has improved the predictability of the noise to be expected at angles exceeding 90^o.

One of the principal results of this analytic study has been to demonstrate the importance of the parameter V_e/V_j in calculation of the sound field emitted by moving jets.

Also, the effect of the jet's propulsion speed manifests itself through a modification of the noise's directional characteristics as compared with stationary jets at angles exceeding 90^o, which may be attributable to the preponderance of the aerodynamic sources of order 0 and 1 .

We have sought to represent this modification, which constitutes *a notable amplification* of the continuous-spectrum noise toward the forepart of the aircraft (not attributable to the compressor), with an experimental and tentative convenient expression for the exponent affecting the convection factor as a function of the flight Mach number. For $\theta > 90^{\circ}$ this exponent is actually a function of many parameters: pressure ratio, Mach number, angle θ , etc.

Translator's Note: The French original concludes with a list of eight errata, i.e., author's corrections, which have been incorporated into this translation.

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